AD________________

Award Number: W81XWH-12-1-0243.

TITLE: Temporal Progression of Visual Injury from Blast Exposure

PRINCIPAL INVESTIGATOR: Brittany Coats, PhD

CONTRACTING ORGANIZATION: University of Utah
SALT LAKE CITY UT 84112-9023

REPORT DATE: September 2013

TYPE OF REPORT: Annual

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;
Distribution Unlimited

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE September-2013	**2. REPORT TYPE** Annual	**3. DATES COVERED** 1 September 2012 – 31 August 2013

4. TITLE AND SUBTITLE

Temporal Progression of Visual Injury from Blast Exposure

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W81XWH-12-1-0243

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Brittany Coats, Daniel Shedd

E-Mail: bcoats@eng.utah.edu; d.shedd@utah.edu

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

UNIVERSITY OF UTAH, THE
201 S PRESIDENT CIRCLE RM 408
SALT LAKE CITY UT 84112-9023

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The purpose of this grant is to investigate the temporal progression of eye injury from blast exposure and identify early predictors of visual dysfunction. We propose to accomplish this by first identifying the probability of military personnel developing visual system injury after blast exposure, and determining the time point after blast exposure that visual system injury becomes identifiable. Next, we propose to systematically evaluate the time course of visual system injury from blast exposure using our existing rat model for blast traumatic brain injury. From the studies performed in the previous year, we have found that low-level blast exposure (~225 kPa) in rats appears to result in a general decrease in visual acuity without any signs of stress or pain in the animals. Scleral hemorrhage was observed upon gross exam.

15. SUBJECT TERMS
Biomechanics, ocular trauma, blast, rats, visual acuity

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** USAMRMC
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	17	**19b. TELEPHONE NUMBER** *(include area code)*

Table of Contents

INTRODUCTION

Ocular trauma during military conflicts has steadily increased from 0.5% in the civil war to 13% in present day. This increase is likely associated with the advancement of weaponry and the increased use of explosive devices. The majority of eye injuries from an explosion can be classified as either open globe or closed globe. Open globe injury is often readily identifiable and typically undergoes urgent surgical repair. However, closed globe injury may not be detected immediately and can result in a series of sequelae that lead to visual dysfunction months after the blast. The progression of closed globe eye injury and visual degradation following blast exposure has not been well characterized. Furthermore, it is unknown if there are early indicators that denote an increased risk for developing visual dysfunction following blast exposure. Therefore, the objectives of this proposal are to investigate the temporal progression of eye injury from blast exposure and identify early predictors of visual dysfunction. We propose to accomplish these objectives by first identifying the probability of military personnel developing visual system injury after blast exposure, and determining the time point after blast exposure that visual system injury becomes identifiable. Next, we propose to systematically evaluate the time course of visual system injury from blast exposure using our existing rat model for blast traumatic brain injury. From these experimental studies we can identify early predictors of visual dysfunction. Finally, we will evaluate these early predictors in a clinic setting to verify their usefulness in real-world scenarios. By understanding the temporal and chemical progression of eye injury from blast exposure, we can establish early identifiers of visual system injury. This will enhance our diagnostic capabilities and lead to the development of time-dependent treatment strategies to mitigate the loss of vision in military personnel.

BODY

Aim 1: Investigate the progression of visual system injury in service members exposed to a blast.

SOW 1: Retrospective analysis of the military personnel with visual system injury attributed to blast exposure but not immediately identifiable at the time of the blast

Obtaining IRB approval from all parties was an unexpectedly long process. The University of Utah IRB approval was obtained Oct. 12, 2012. The VA Hospital of Salt Lake City IRB approval was obtained Mar 28 2013. The HRPO IRB approval was obtained June 28, 2013. To speed up the subsequent tasks for this aim, a project coordinator and medical student were hired. Since all approvals were obtained, a formal request for MR#s has been made to the University of Utah Hospital. Results from the query are currently being evaluated. Accessing veteran hospital records proved to be more challenging. To overcome this issue, the PI recently met with the polytrauma group at the VASLC. A collaboration was established to identify blast victims from their databases. Current security approvals are being sought and record evaluation will begin late October. It is anticipated that the study will only be delayed by 3-5 months.

Aim 2: Investigate the progression of visual system injury following blast exposure in an animal model and identify early indicators of visual dysfunction.

SOW 1: Manufacture new blast device with enhanced mach stem overpressure capabilities.

The shock tube for the experimental studies was purchased from AgileNano (Fig 1a-b). It has a 6” internal diameter and 15’ length, which is sufficient for blast testing in the rat model. The shock tube is instrumented with side-on mounted PCB 113B26 pressure transducers (PCB Piezotronics, NY) installed every two feet along the driven section (Fig 1c). These sensors can measure up to 500 psi and are monitored at 1 MS/s via Labview (National Instruments, TX). Extensive work was done to set up and validate the behavior of the shock tube. This included characterizing the shock tube across a range of driver pressures and membrane thicknesses (Fig.2). Additionally, work was done to devise an appropriate filtering system to acquire clean pressure data from the transducers. After extensive filter design using spectral analysis, a cutoff frequency of 275 kHz was selected. Upon data collection, the pressure signal passed through an analog anti-aliasing low pass filter (Fig. 3). A digital 50 kHz filter was then implemented post-hoc in MATLAB. This protocol was found to eliminate the majority of the noise without significantly decreasing the peaks of the signal.

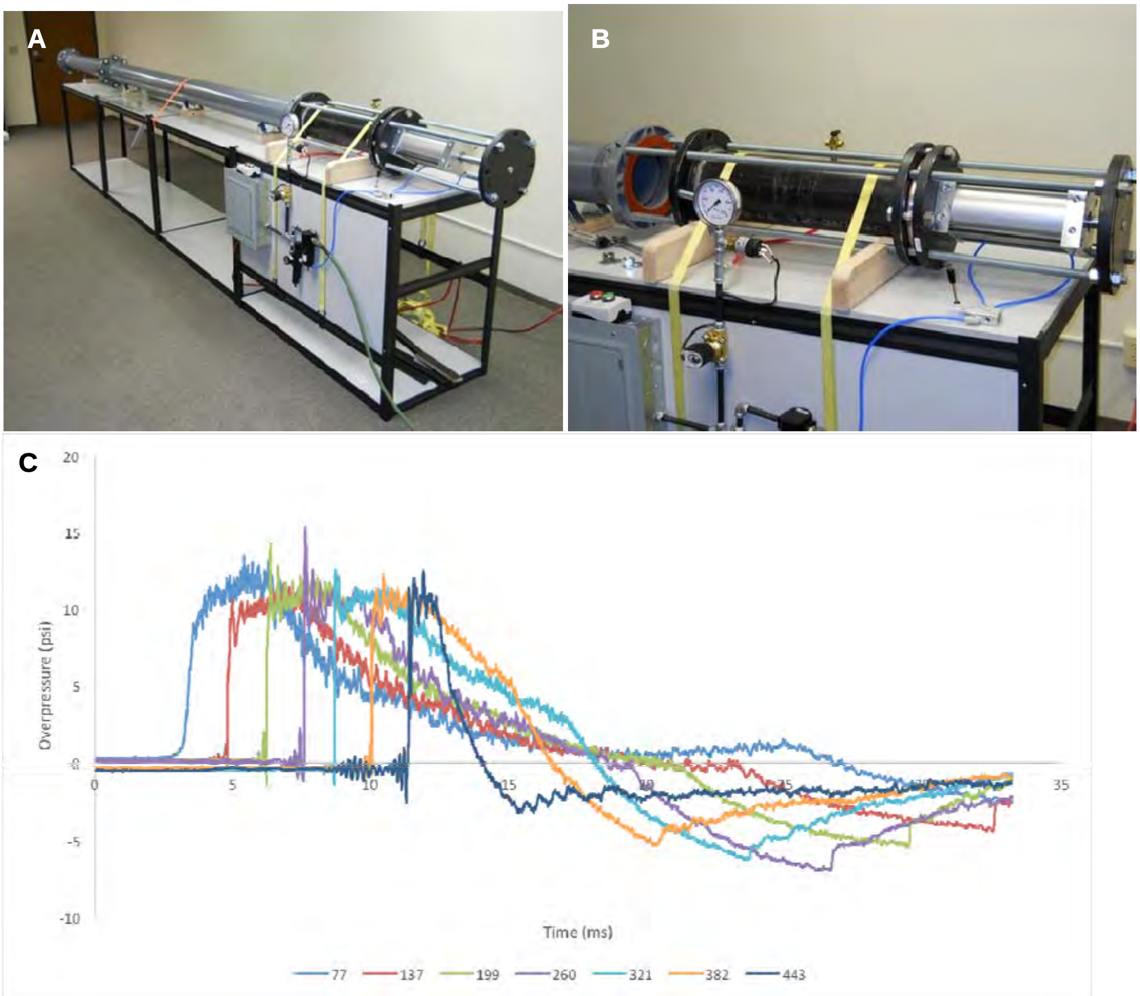


Figure 1. (A) Shock tube purchased for blast studies. (B) Close-up of the driver section of the shock tube. (C) Overpressure recorded at seven locations along driven section

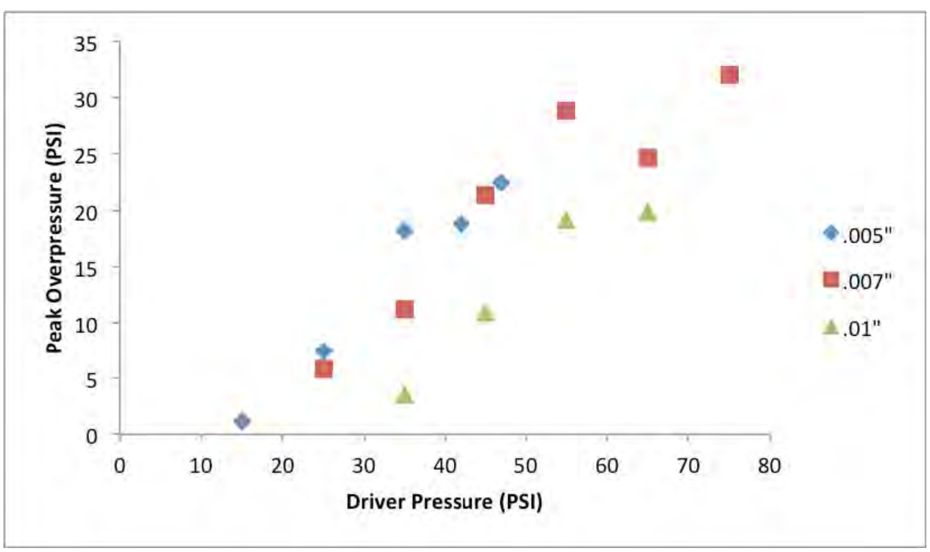


Figure 2. A variety of membrane thicknesses were evaluated to determine the appropriate experimental conditions for the desired peak overpressures.

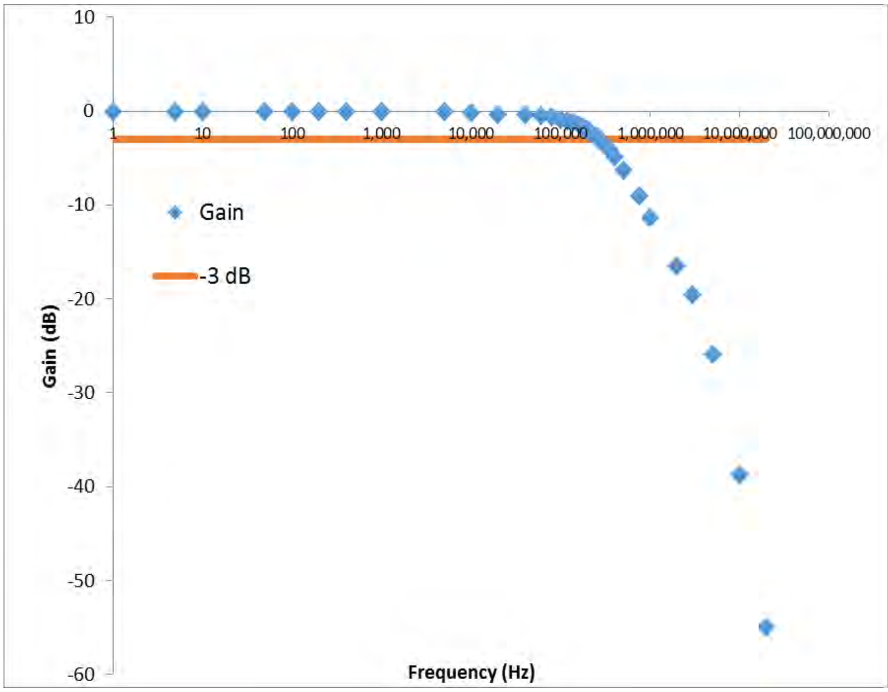


Figure 3. Bode plot for the final anti-aliasing filter built for the shock tube system.

Characterization also included creation of a finite element model of the shock tube to examine the behavior of the shock tube with different driver gases and to determine the appropriate location for rate placement (Appendix A). We also verified that the blast wave produced by the shock tube appropriately modeled the Friedlander wave, which is characteristic of open-field blasts.

A decision was made to place the animal inside of the shock tube rather than outside of the muzzle. This allows the blast exposure to have a duration of approximately 2-8 msec. It also reduces the variability in shock tube strength inherent to placement outside the shock tube. A rat holder was designed and 3-D printed to allow for a test animal to be placed securely within the blast tube and subjected to a side-on blast (Fig. 4). The primary design consideration was allowing blast exposure to the head while preventing blast trauma to the torso as lung damage may be fatal at the blast levels currently being used. The protective measures include placing the body of the animal outside the path of the blast wave and wrapping the body in a Kevlar vest for further protection. Initial animal experiments have not shown any signs of lung damage so these measures have been deemed successful. Low vibration of the mount was verified by placing linear accelerometers onto the mount and measuring motion during a blast with no animal in the tube. A maximum displacement of <0.5 mm was recorded.

To ensure the safety of the operators of the device, ear protection is worn during use of the shock tube. However, a recent inspection found that decibel levels outside of the blast room were too high. We are currently in the process of manufacturing a sound absorption chamber for the end of the shock tube (Fig. 5). Testing is underway to ensure sound outside of the blast room is reduced and the pressure profile is unaffected.

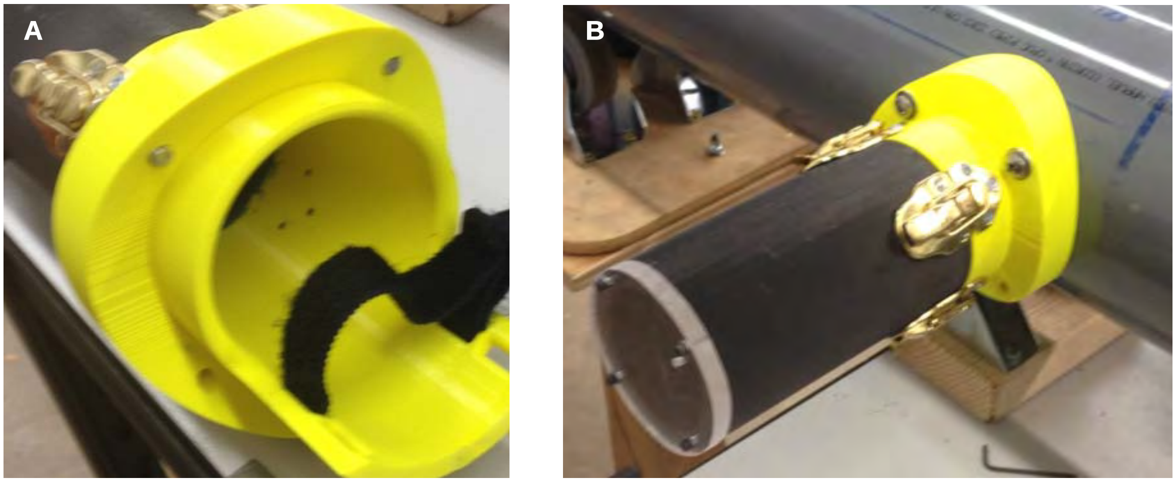


Figure 4. (A) Animal mount designed to place the head inside the shock tube and position it for a lateral blast exposure. (B) The end of the mount is clear in order to monitor the respiration of the rat during the blast.

Figure 5. A sound absorption chamber was designed and installed to the end of the shock tube (A) to decrease the decibel level of the shock tube. (B) The chamber is lined with sound absorbing foam.

SOW 2: Establish randomized testing protocol for 12 experimental groups: 4 severities of blast exposure (140kPa, 260kPa, 450kPa, and control) each with 3 survival periods (1 day, 1 week, 4 weeks).

Post-injury time following blast exposure is the most important factor of the study and new literature suggested that 4 weeks may not be long enough to explore. Therefore, we increased the number of survival periods to 4 (1 day, 2 weeks, 4 weeks, 8 weeks) and decreased the number of blast levels explored to 2 (control, 225 kPa and 450 kPa). We have already begun to see some ocular injury at the low blast level.

SOW 3: Complete experimental studies investigating temporal changes of visual system injury from blast exposure. (Year 1-Year 3)

To verify that our experimental design (Fig. 6) will result in a low mortality rate, the low blast level is being evaluated first before proceeding to the high blast level. Briefly, animals are administered carprofen one day before the blast for pain management. A baseline of vision functionality is established before the blast using the metrics detailed in SOW 4. On the day of the blast, the animal is anesthetized using ketamine/xylazine or ketamine/dexmetomedine and placed in the holder within the shock tube. A pressure wave is initiated. The animal is removed from the device, allowed to recover from the anesthesia, and then returned to the animal facility. While animals do not show signs of pain following the blast exposure, carprofen is administered the next day as a precaution. The vision metrics are then repeated the day after the blast and every subsequent week following the blast until sacrifice (see SOW 4). At sacrifice, the eyes and brain are harvested for later analysis (see SOW 5). To date, 5 animals have been evaluated (1 2-week survival, 2 8-week survivals, and 2 blast characterization). It is anticipated that 40 animals will be evaluated by Dec 2013.

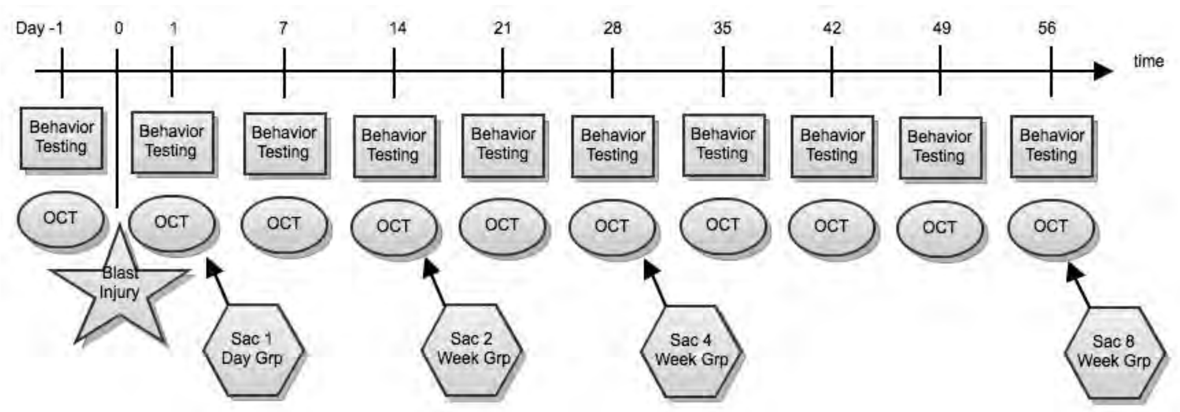


Figure 6. Procedural timeline for blast animal studies and vision testing.

Two animals were used to determine the effect of the blast on intraocular pressure (IOP). The IOP sensors used for these studies were damaged due to the high pressure loads. We are currently reviewing new pressure systems to continue these characterizations.

SOW 4: Complete animal OCT and behavior studies to test visual function on all animals prior to blast exposure and at 1 day, 1 week, or 4 weeks post injury. (Year 1-Year 3)

<u>Behavior Testing: Optokinetic Tracking Test</u>

In Year 1, the behavioral test system was designed, built, and programmed. The system is made up of four television monitors to display the visual stimulus to the animal in 360 degrees of rotation (Fig. 7a) Behavior is monitored using a closed circuit video system. The coding to control and display the behavioral stimulus was created in-house using MATLAB software (Mathworks, MA) with the psychtoolbox software package. The output of the behavioral system is an estimate of the visual acuity threshold from zero (best) to one (worst). The relative visual acuity is tracked week to week to identify visual degradation (Fig. 7b). For increased accuracy, each animal is tested three times at each testing day so that an averaged acuity may be calculated with measures of uncertainty.

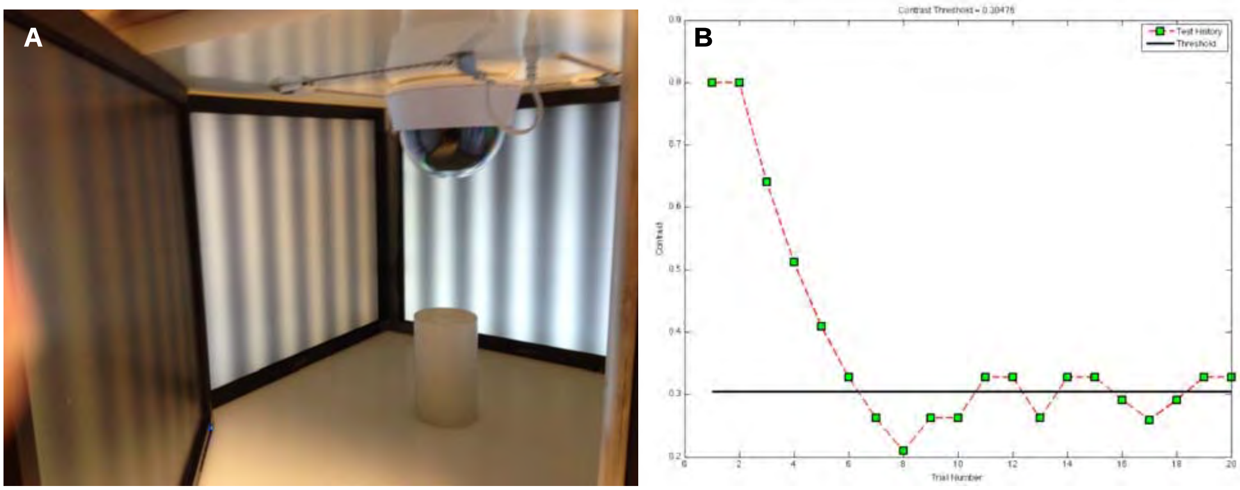


Figure 7. An optokinetic system was built to test the visual change in the rats over time. (A) The system consists of 4 LCD screens which vary the black and white contrast bars throughout the test. (B) Visual acuity is assessed by the rat's ability to see the distinction between the black and white bars. The program automatically adjusts the contrast until an equilibrium is reached.

<u>Optical Coherence Tomography (OCT)</u>

OCT can be used to image the retinal and evaluate changes in retinal thickness. A thinning of this layer is often reported to be associated with visual dysfunction. Furthermore, histological findings such as retinal hemorrhages or retinal detachments can be detected using this technique.

An Envisu R220 Spectral Domain OCT (Bioptigen, Durham, NC) system was acquired, along with a lens specific to the focal length of the rat eye. An imaging protocol was developed to generate a clear image of left and right eyes, each centered on the optic nerve. Rats are anesthetized by inhalation of 4% isoflurane, and the pupils are dilated with 1% tropicamide. The OCT images (Fig. 8) will be analyzed using either in-house thickness measurement or the automated Diver 2.0 software from Bioptigen.

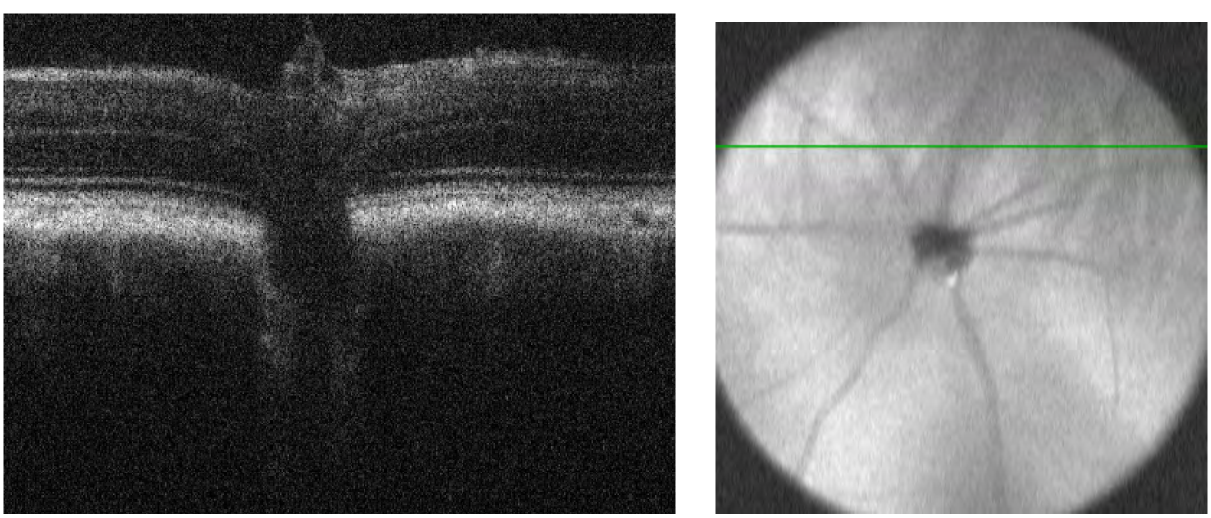


Figure 8. Optical coherence tomography (OCT) is used to monitor changes in the retinal thickness (A). A series of retinal images are taken in a radial pattern around the optic nerve of the eye (B).

Visual Evoked Potential (VEP)

VEP was added to the protocol to help distinguish between eye injury and injuries to the optic nerve or visual cortex. Briefly, eyes are exposed to a light stimulus and resulting visual cortex activity is measured. The light stimulus is made up of 10 white LEDs with 0.064 watts per LED. Each stimulus consists of a half second duration light pulse from the array followed by no less than a half second period during which the array is off. The stimulus is repeated 15 times for each eye. The brain signal from the visual cortex is measured using Ag/Cl electrodes (Grass Technologies, RI). The signal is collected, fed through an amplifying circuit (built in-house), and then recorded using LabView. The signal is filtered post-hoc, segmented, averaged, and analyzed in MATLAB. A bandpass filter (1-100 Hz) and notch filter (60 Hz) are used to isolate the desired brain waves. The program isolates and averages the 15 repeated signals for each eye to eliminate portions of the signal not directly related to the VEP (Fig. 9). The primary metrics recorded for the VEP are the peak positive and negative amplitudes as well as the delay between stimulus and peak response. Our initial studies with VEP resulted in a low signal amplitude. This is likely due to the effect of the anesthesia on the brain signal. For future studies, we have switched from ketamine to isoflurane as the anesthetic.

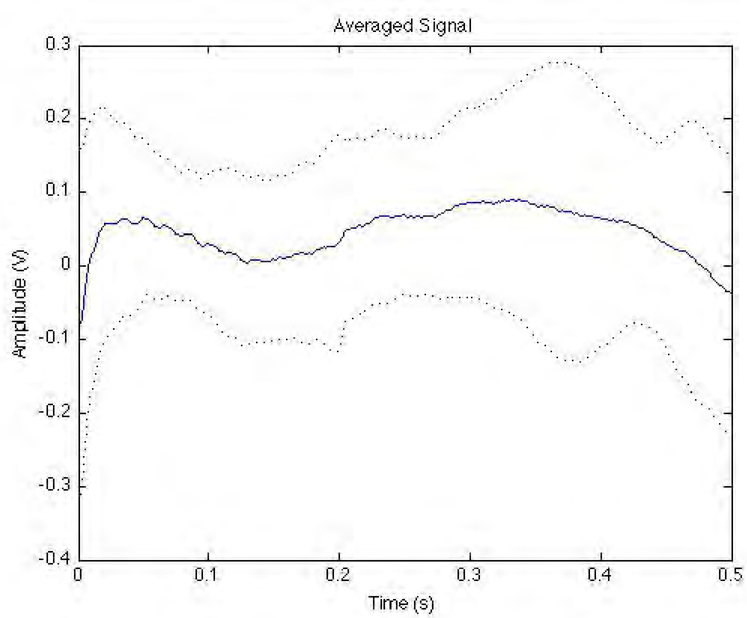


Figure 9. Visual cortex signals fom VEP. Fifteen signals are averaged to determine the brain response to visual stimulation.

SOW 5: Complete histology for ocular injury from blast exposure (Year 1 - Year 3)

Following euthanization at the appropriate time points, animals are perfusion fixed with 10% formalin. The brains are extracted and stored in 10% forrmalin. The eyes are extracted and stored in a mixture of 2% gluteraldehyde and 2.5% formaldehyde. Both tissues will be processed for axonal injury and ocular trauma.

Aim 3: Identify changes in vitreous protein expression that correlate with visual system injury

SOW 1: Collect vitreous samples following every animal experiment in Aim 2. (Year 1-Year 3)

The eyes from half of the animals in each group will be used to evaluate cytokine biomarkers of ocular trauma. Currently, eyes have been removed from animals in the first group and are being stored in a -70°C freezer until the protocol for protein analysis is validated.

SOW 2: Assay samples for NfH (a marker for retinal deterioration), VEGF, IL-10, MCP-1, and MIP-3. (Year 1-Year 3)

The protocol to perform the assays is currently in development. Equipment purchase for sample analysis is underway.

KEY RESEARCH ACCOMPLISHMENTS:

- Acquired shock tube
- Characterized pressure profile throughout tube both experimentally and computationally
- Added animal mount to shock tube
- Determined and created robust filtering protocols for pressure signals
- Designed, programmed and manufactured vision behavior system for rats
- Purchased OCT and developed a successful imaging protocol
- Added VEP to enhance interpretation of results
- Build VEP system and developed appropriate filtering protocol
- Began blast animal studies
- Began IOP characterization from blast
- Received animal use approval from University of Utah and Department of Defense
- Received human study IRB approval from University of Utah, Veterans Hospital of Salt Lake City, and Department of Defense.
- Developed a collaboration with the polytrauma group at the VASLC to obtain access to medical records of military personnel involved in a blast.
- Submitted requests for medical record numbers of blast victims treated at the University of Utah hospital.

REPORTABLE OUTCOMES:

In YEAR 1 of project, the work has been presented at two conferences:

- 11th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering (Appendix A & B)
- 9th Annual Utah Biomedical Engineering Conference (Appendix c)

The work was also presented to the polytrauma group at the veterans hospital in Salt Lake City (Appendix D)

CONCLUSION: The successful completion of the studies proposed in this 4 year project will form the basis for understanding the temporal and chemical progression of visual system injury following blast exposure. In the first year, all the infrastructure and product development was completed to successfully achieve the stated goals of the study. Clinical and experimental work is underway. The proposed project was enhanced by custom-making the vision behavior device and adding visual evoked potential to the battery of tests. Once completed, the results from these studies will lead to earlier diagnoses of visual system injury, expand our understanding of the time-dependent response of the visual system to blast, and help identify treatment options for mitigating vision loss from blast exposure.

APPENDICES:

- Appendix A – Abstract accepted to the 11th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering
- Appendix B – Poster presented at the 11th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering
  Appendix C – Abstract accepted to the 9th Annual Utah Biomedical Engineering Conference
- Appendix D – Powerpoint presentation to the VA Polytrauma group.

Proceedings of the 11th International Symposium,
Computer Methods in Biomechanics and Biomedical Engineering
April 3 - 7, 2013, Salt Lake City, Utah, USA

VERIFICATION OF A SHOCK TUBE FINITE ELEMENT MODEL FOR BLAST OCULAR INJURY SIMULATIONS

Daniel F. Shedd and Brittany Coats

Department of Mechanical Engineering
University of Utah
Salt Lake City, Utah, USA

INTRODUCTION

Blast exposure is a leading cause of eye injury for the US Army [1]. Typically, ocular injury occurs from explosive shrapnel and debris, but recently many soldiers have developed vision deficits 6-12 months following a blast exposure without any signs of injury [2]. To better understand the mechanisms behind blast induced eye trauma and subsequent vision loss, we propose to develop a finite element (FE) model of an eye exposed to pressure waveforms associated with blast. As a first step toward this model, we sought to develop an accurate representation of the shock wave pressure profiles associated with real world blast exposure. Therefore, the primary objective of this study was to develop and validate the shock tube FE model to be used in the eye blast simulations. A secondary objective of this study was to identify the shock tube design criteria required to generate the desired pressure profiles for experimental ocular blast studies in rats. These experimental data will be used to validate the future eye blast simulations.

METHODS

To simulate the pressure profiles in the shock tube, an Eulerian analysis was selected. Helium, hydrogen, and air were used as driver section gases. Air was used in the driven section (Figure 1). Each gas was represented using the ideal gas equation of state. Material properties used in the model are listed in Table 1. Initial gas assignment for the Eulerian mesh was performed using reference cylinders. Temperature was used to set the initial pressures of the gas for each of the tube sections. The open-ended shock tube was represented as a rigid body with an outer diameter of 1.52 cm and a length of 4 m. This length was broken up into a 1 meter driver section and a 3 meter driven section. The effect of gravity was considered negligible. The membrane separating the tube sections was not included in the model because the time period investigated was immediately subsequent to membrane rupture.

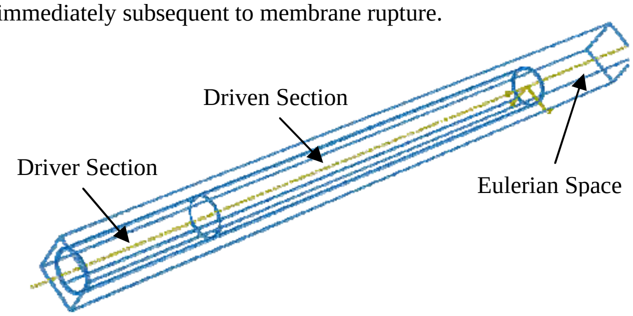


Figure 1. Geometric and Eulerian sections of the finite element model.

The Eulerian space was meshed with linear hexahedral elements and analyzed in ABAQUS/Explicit (Dassault Systemes, Paris). A convergence study was performed using a driver gage pressure of 256.1 kPa to match previous simulations [3]. Convergence of peak overpressure was assessed using six mesh densities (from 2500 to 925,344 elements) at 2.5 and 5 ms post-rupture. The analysis was performed along the central axis of the driven section. Convergence simulation results were compared to theoretical shock tube calculations [4]. A deviation less than 5% from the theoretical calculations was considered acceptable.

	Density kg/m3	Dynamic Viscosity kg/m-s	Gas Constant J/kg-K	Specific Heat J/kg-K
Air	1.177	1.85E-05	287	716
Helium	0.16674	1.96E-05	2077	3120
Hydrogen	0.0899	8.75E-06	4126	10185

Table 1. Ideal Gas properties for air, helium, and hydrogen.

Pressure values (integration point, gage pressure) generated by a 200 kPa initial driver overpressure were recorded along the entire length of the central axis of the driven section from 0 to 12 ms post-rupture (Figure 3). The peak overpressure every 10 cm was extracted.

Simulations of three driver gases (air, helium, and hydrogen) were run (Figure 4). The peak overpressure, peak overpressure duration (defined as pressure >.95 peak value), and time constant (pressure >.632 peak) for each driver gas was recorded at the central axis of the tube at the longitudinal midpoint of the driven section (1.5m from muzzle). The location was chosen to allow enough space from the driver section for the shock wave to fully form while allowing enough distance from the tube mouth to collect meaningful data. For each driver gas, initial temperature conditions were selected such that initial driver overpressure was 200 kPa.

RESULTS

The model converged to within 1.5% from the analytical prediction. The density of the final Eulerian mesh was 338676 nodes and 312500 elements. An example simulation result at t=1.8 ms is shown in Figure (2). Peak overpressure of the wave decreased as the shock wave traveled down the tube (Figure 3). The rate of the decrease was -4.7 kPa/m. Hydrogen gas resulted in the highest peak overpressure at 131.0 kPa (helium: 124.4 kPa; air: 92.0 kPa.) and the shortest peak overpressure at 75.2 µs (helium: 199.4; air: 774.5). The time constants of the pressure waves resulted in a similar trend: Hydrogen .550 ms, Helium .687 ms, Air 2.926 ms (Figure 4).

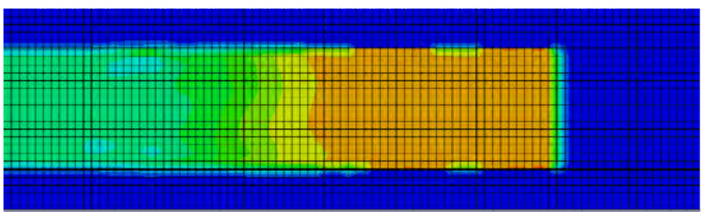


Figure 2. Cross-section view of overpressure at shock front, t=1.8 ms. Data was recorded along midline elements.

DISCUSSION

Peak shockwave overpressure diminished as the shockwave traveled towards the mouth of the tube. The trend was -4.7 kPa/m, which equates to a loss of 14.1 kPa over the length of the driven section, or 10.4% of initial driven section overpressure. Shock tube theory indicates that the shock wave overpressure should remain constant throughout the driver section after the initial 30-50% of the tube. Real shock tubes do exhibit diminishing overpressure along the tube due to boundary effects and energy dissipation.

Changing the driver gas impacted the peak overpressure, peak duration, and time constant of the resulting shock waves. Light gases (Helium, Hydrogen) behaved closer to ideal gases and better approximated the Friedlander waveform.

The environment outside of the shock tube was not modeled. Therefore, when the shock wave nears the end of the tube the accuracy of the data cannot be ensured. By observation of trends in the data, the last 10% (30 cm) of the tube appears to have been affected. This suggests that test subjects used to develop validation data for the future eye blast simulations must be positioned prior to this location.

Membrane rupture was assumed to occur immediately prior to simulation. Real membranes rupture by splitting into flaps of material which partially impede gas flow and introduce asymmetry into the shock front. Membrane scraps can also be carried down the tube with the shock front or the subsequent air jet. In this simulation, rupture was modeled as if the membrane disappeared upon rupture.

Future studies will place an eye model within the simulated shock tube and track the pressure inside and outside of the eye over time, as well as the strain that develops within the eye. These data will be associated with experimental visual dysfunction experiments from blast exposure. Characterization of the decrease in overpressure along the length of the tube will be used to determine the ideal placement of test subjects. The driver gas results will be used to fine tune the magnitude and duration of the blast shock wave.

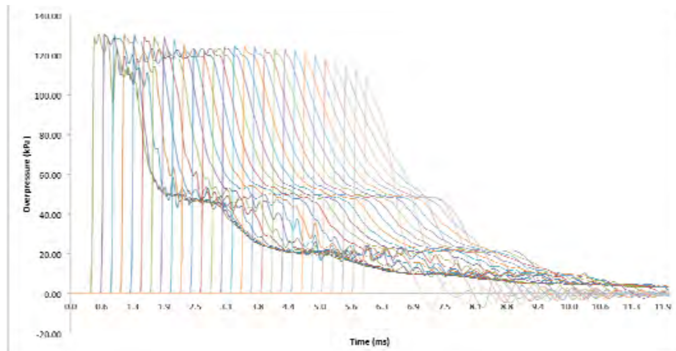


Figure 3. Pressure time profiles. Curves represent 10 cm of driver length. Note the decrease in peak overpressure.

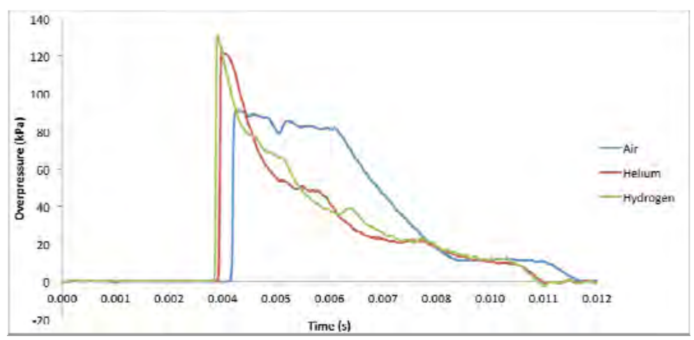


Figure 4. Shock wave at midpoint of driver section for air, helium, and hydrogen driver gases.

ACKNOWLEDGEMENTS

We'd like to thank USAMRMC #W81XWH-12-1-0243 for their generous support of this work.

REFERENCES

[1] DeFraites, R et al., Medical Surveillance Monthly Report, May 2011: 2-6. 2011.
[2] Cockerham, G., *et al.* Eye and visual function in traumatic brain injury. *Journal of Rehabilitation Research and Development* **46**, 811-818 (2009).
[3] Carlucci, P et al., 2010 Simulia Customer Conference.
[4] Torrilhon M et al., Proc. 8th Intl. Conf. Hyperbolic Problems 2000.

Verification of a Shock Tube Finite Element Model for Blast Ocular Injury Simulations

Daniel F. Shedd and Brittany Coats, PhD

Mechanical Engineering, University of Utah, Salt Lake City, UT USA

Introduction

Blast exposure is a leading cause of eye injury for the US Army [1]. Typically, ocular injury occurs from explosive shrapnel and debris, but recently many soldiers have developed vision deficits 6-12 months following a blast exposure without any signs of injury [2]. To better understand the mechanisms behind blast induced eye trauma and subsequent vision loss, we propose to develop a finite element (FE) model of an eye exposed to pressure waveforms associated with blast. As a first step toward this model, we sought to develop an accurate representation of the shock wave pressure profiles associated with real world blast exposure. Therefore, the primary objective of this study was to develop and validate the shock tube FE model to be used in the eye blast simulations. A secondary objective of this study was to identify the shock tube design criteria required to generate the desired pressure profiles for experimental ocular blast studies in rats.

Methods

To simulate the pressure profiles in the shock tube, an Eulerian analysis was selected. Helium, hydrogen, and air were used as driver section gases. Air was used in the driven section (Fig. 1). Each gas was represented using the ideal gas equation of state. The open-ended shock tube was represented as a rigid body with an outer diameter of 15.2 cm and a length of 4 m. The effect of gravity was considered negligible. The membrane separating the tube sections was not included in the model because the time period investigated was immediately subsequent to membrane rupture.

The Eulerian space was meshed with linear hexahedral elements and analyzed in ABAQUS/Explicit (Dassault Systemes, Paris). A convergence study was performed using a driver gage pressure of 256.1 kPa to match previous simulations [3]. Convergence results were compared to theoretical shock tube calculations [4]. A deviation less than 5% from the theoretical calculations was considered acceptable.

Pressure values (integration point, gage pressure) generated by a 200 kPa initial driver overpressure were recorded along the entire length of the central axis of the driven section from 0 to 12 ms post-rupture. The peak overpressure every 10 cm was extracted.

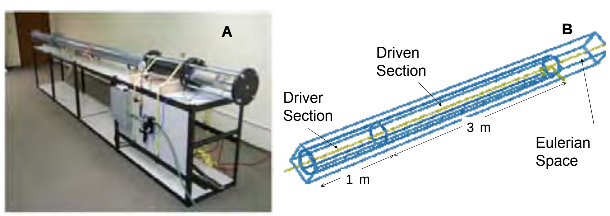


Figure 1. (A) Experimental shock tube. 6" internal diameter. Blast triggered via pneumatically activated arrowhead rupturing BoPET membranes of varied thickness. Instrumented with 1 MS/s pressure sensors (PCB 113B26) along the length of the driven section. **(B)** Geometry of finite element model.

Driver Gas	Density (kg/m³)	Dynamic Viscosity (kg/m-s)	Gas Constant (J/kg-K)	Specific Heat (J/kg-K)
Air	1.177	$18.5*10^{-6}$	287	716
Helium	.16674	$1.96*10^{-6}$	2077	3120
Hydrogen	.0899	$8.75*10^{-6}$	4126	10185

Table 1. Ideal Gas properties for air, helium, and hydrogen driver gases. Air was used as the driven section gas for all simulations.

Results

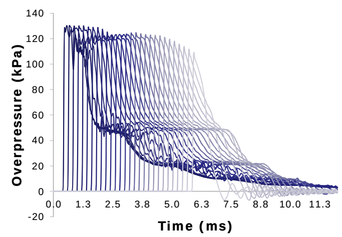


Figure 2. Pressure time profiles. Each curve represents history output of single element. One curve generate for each 10 cm along the driven section. Peak overpressure decreased as a function of distance.

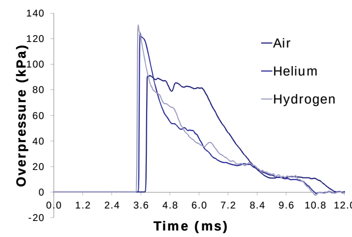


Figure 3. Shock wave at midpoint of driver section for air, helium, and hydrogen driver gases. Each curve represents the overpressure at one element across time. The peak overpressure increased with decreasing driver gas density.

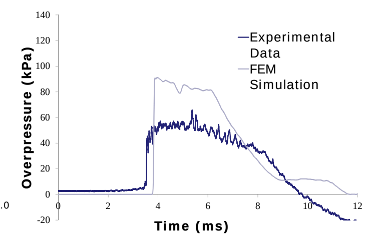


Figure 4. Comparison of result from FEM simulation and results from experimental shock tube with 200 kPa driver pressure. Experimental blast produced low overpressure due to membrane inefficiency. Blast duration was accurately predicted.

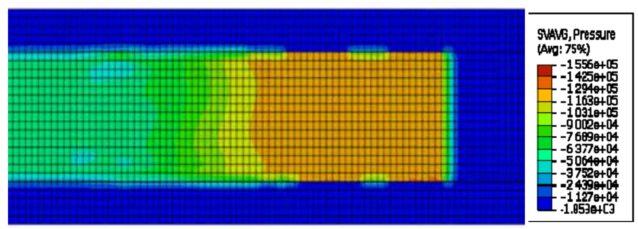


Figure 5. Cross-section view of overpressure (Pa) of the shock front at t=1.8 ms. This simulation used a helium driver gas with initial pressure set to 200 kPa (29 psi). Data was recorded along central axis elements for analysis to avoid edge effects near the boundary of the tube.

The model converged to within 1.5% from the analytical prediction. The density of the final Eulerian mesh was 338676 nodes and 312500 elements. Peak overpressure of the wave decreased as the shock wave traveled down the tube (Fig. 2). The rate of the decrease was -4.7 kPa/m. Hydrogen gas resulted in the highest peak overpressure at 131.0 kPa (helium: 124.4 kPa; air: 92.0 kPa, Fig. 3) and the shortest peak overpressure at 75.2 μs (helium: 199.4; air: 774.5). The time constants of the pressure waves resulted in a similar trend: Hydrogen .550 ms, Helium .687 ms, Air 2.926 ms. The 200 kPa simulation was validated against shock tube data from a 200 kPa blast with air as the driver gas (Fig. 4). A cross-section view of pressure within the driven section is shown in Fig. 5.

Conclusion

The Eulerian shock tube simulation was successful in capturing the development of a Friedlander wave as the shock wave traveled down the tube. Additionally, distinct differences in peak overpressure and pressure wave duration could be seen. These simulations will assist in the design of future experimental studies investigating vision loss from blast exposure. FEM simulations were also able to capture the time duration of actual experimental data, but overestimated peak overpressure. This is likely due to the effect of membrane rupture on the peak overpressure, which was not incorporated into the model.

Future studies will place an eye model within the simulated shock tube and track the intraocular pressure (IOP) over time, as well as the strain that develops within the eye. These data will be associated with experimental visual dysfunction experiments from blast exposure. Characterization of the decrease in overpressure along the length of the tube will be used to determine the ideal placement of test subjects. The driver gas results will aid in selecting appropriate driver gas for desired overpressure magnitude and duration parameters. This model provides a tool for experimental design for blast studies using shock tubes and for simulating the effects of blast on biological structures.

References

[1] DeFraites, R et al., Medical Surveillance Monthly Report, May 2011: 2-6. 2011.

[2] Cockerham, G., *et al.* Eye and visual function in traumatic brain injury. *Journal of Rehabilitation Research and Development* 46, 811-818. 2000.

[3] Carlucci, P et al., "Validation of Abaqus Explicit – CEL for classes of problems of interest to the U.S. Army" 2010 Simulia Customer Conference.

[4] Torrilhon M et al., "The Riemann-Problem in Extended Thermodynamics." Proc. 8th Intl. Conf. Hyperbolic Problems 2000.

Acknowledgements

We would like to thank *USAMRMC #W81XWH-12-1-0243* for support of this project .

Contact Information

Daniel F. Shedd
Email: d.shedd@utah.edu

Brittany Coats, PhD
Email: brittany.coats@utah.edu

APPENDIX B - Poster presented at 11th International CMBBE

Appendix C – Abstract accepted to the 9th Annual Utah Biomedical Engineering Conference

Blast exposure is a leading cause of eye injury for the US Army. Typically, ocular injury occurs from explosive shrapnel and debris, but recently many soldiers have developed vision deficits 6-12 months following a blast exposure without any signs of injury. To better understand the mechanisms behind blast induced eye trauma and subsequent vision loss, we propose to develop a finite element (FE) model of an eye exposed to pressure waveforms associated with blast. As a first step toward this model, we sought to develop an accurate representation of the shock wave pressure profiles associated with real world blast exposure.

APPENDIX D - Powerpoint presentation to the VA polytrauma group.

Head & Eye
Injury Biomechanics Lab

Objectives: Utilize principles and tools of engineering to understand biomechanics and develop injury tolerances for head and eye.

Tools/Skills: Mechanical testing, imaging, animal models of injury, finite element modeling.

Brittany Coats, PhD brittany.coats@utah.edu www.mech.utah/pedtrauma

---

Head & Eye
Injury Biomechanics Lab

Visual Injury from Blast Exposure

- 13% of all battlefield injuries in Operations Iraqi and Enduring
  - Open vs. closed globe injury
- ~75% of soldiers with traumatic brain injury also have visual dysfunction

Brittany Coats, PhD brittany.coats@utah.edu www.mech.utah/pedtrauma

---

Head & Eye
Injury Biomechanics Lab

Progression of visual dysfunction following blast exposure

Experimental Studies

- Determine blast mechanics associated with ocular injury
- Identify timelines of ocular injury
- Determine early identifiers of visual injury

Clinical Studies

- Characterize ocular injuries associated w/ and w/out TBI
- Identify timelines of injury diagnosis/awareness
- Determine early identifiers of visual injury

Funded by USAMRAA Vision Research Program

Brittany Coats, PhD brittany.coats@utah.edu www.mech.utah/pedtrauma

---

Head & Eye
Injury Biomechanics Lab

Project Team

Experimental

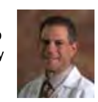
Brittany Coats, PhD - PI
Assistant Professor
Mechanical Engineering

Ken Monson, PhD
Assistant Professor
Mechanical Engineering

Clinical

Jason Goldsmith, MD
Ophthalmology
Moran Eye Institute, VAHC

Bradley Katz, MD PhD
Neuro-ophthalmology
Moran Eye Institute



Dan Shedd
Doctoral Candidate
Mechanical Engineering

Brian Zaugg, MD
Ophthalmology Resident
University of Utah

Amith Subhash
Medical Student
University of Utah

Funded by USAMRAA Vision Research Program

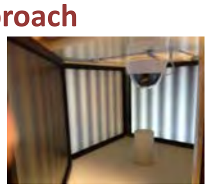
Brittany Coats, PhD brittany.coats@utah.edu www.mech.utah/pedtrauma

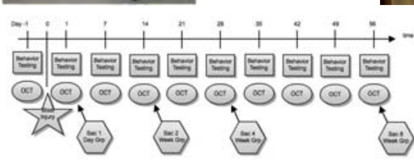
---

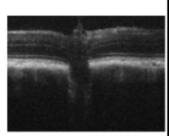
Head & Eye
Injury Biomechanics Lab

Experimental Approach

- Optokinetics
- OCT
- Visual Evoked Potential
- Vitreous biomarkers
- Histology







Brittany Coats, PhD brittany.coats@utah.edu www.mech.utah/pedtrauma

---

Head & Eye
Injury Biomechanics Lab

Clinical Approach

Step 1 – Retrospective review

- Identify people with a history of blast exposure and visual exams
- Record complaints of vision issues and/or diagnosed issues
- Record presence/absence of visual degradation of disorders
- Record time after exposure that visual disorder diagnosed

Step 2 – Prospective study

- Enroll people who have been exposed to a blast
- Record all information known about blast (date occurred, distance from source, cause of blast)
- Perform ocular exams (OCT, optokinetics, etc) every 6 months for up to 2 yrs.
- Record self-assessed vision questionnaires every 6 months for up to 2 yrs.

Funded by USAMRAA Vision Research Program

Brittany Coats, PhD brittany.coats@utah.edu www.mech.utah/pedtrauma